Measurements With AC Dipoles*

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Abstract

Two AC dipoles with horizontal and vertical oscillating magnetic fields will be installed in RHIC. Both of the magnets are expected to be able to induce maximum 5σ coherent oscillations in the two transverse planes. This is desired for measuring betatron functions and phase advances in the machine as well as for nonlinear beam dynamic studies. The AC dipole with horizontal magnetic field will also be used as a spin flipper for RHIC polarized proton experiments. This paper discusses the possible measurements with the AC dipoles in RHIC.

1 INTRODUCTION

In accelerators, coherent oscillation can be excited by an AC dipole oscillating magnetic field ΔB where

$$\Delta B = \Delta B_{\rm m} \cos \nu_m \phi(s). \tag{1}$$

Here, $\Delta B_{\rm m}$ is the magnetic field oscillating amplitude, $\nu_{\rm m} = \frac{f_{\rm m}}{f_{\rm rev}}$ is the modulation tune where $f_{\rm m}$ is the AC dipole oscillating frequency and $f_{\rm rev}$ is the beam revolution frequency, and $\phi(s)$ is azimuthal angle along the accelerator. The amplitude of the coherent oscillation is determined by the AC dipole field strength and frequency. In an accelerator without any nonlinear components, the coherent oscillation amplitude is given by Eq.(2).

$$Z_{\rm coh} = \sqrt{2\beta_z J} = \frac{\Delta B_{\rm m} \ell}{4\pi (B\rho)|\nu_{\rm m} - \nu_{\rm z}|}\,\beta_z. \tag{2}$$

With a fixed magnetic field amplitude, the closer the AC dipole frequency is to the intrinsic beam betatron oscillation $\nu_{\rm z}$, the stronger the coherent oscillation is. When the AC dipole is right at resonance, the beam then becomes unstable. Here, we use z to stand for either horizontal coordinate or vertical coordinate. β_z is the betatron functions where the dipole is located and $B\rho$ is the magnetic rigidity.

The advantage of using an AC dipole to induce a coherent oscillation is that it can be done in an adiabatic fashion as we have already demonstrated in the Brookhaven AGS[1, 2]. Fig. 1 is experimental data taken during the AGS AC dipole experiment with gold beam. The measured transverse beam size before the AC dipole was turned on and after it was turned off shows that by slowly turning the magnet on and off, the beam emittance remained unperturbed during the whole process. In this way, the length of this sustained coherent excitation is also controllable. This non-destructive manipulation of the beam then allows one to perform beam studies or diagnostics without continuously reinjecting beam and interrupting the normal machine operation.

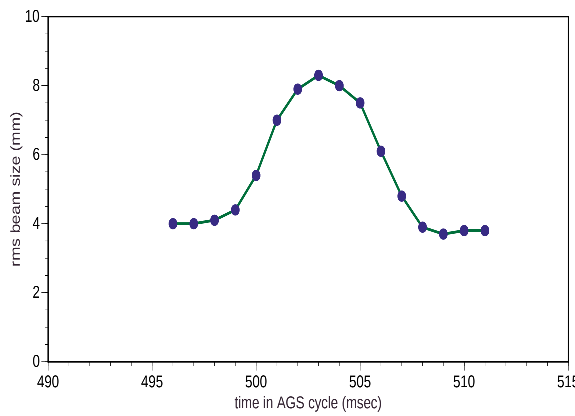

Figure 1: Measured vertical rms beam size as a function of time during the AGS AC dipole experiment with gold beam. The time span covers the whole AC dipole operation process.

2 AC DIPOLE APPLICATIONS

2.1 Measure betatron function and phase advance

The betatron functions and phase advances are measured by analyzing turn by turn beam position data from two beam position monitors (BPMs). The transfer matrix between the two BPMs with the AC dipole excluded in between is given by

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(c+\alpha_1 s) & \sqrt{\beta_1\beta_2}\,s \\ -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}s + \frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}c & \sqrt{\frac{\beta_1}{\beta_2}}(c-\alpha_2 s) \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} \tag{3}$$

where $c = cos\phi_{21}$, $s = sin\phi_{21}$ and the AC dipole is not in between. Therefore, x_1' can then be expressed by the positions at the two BPMs, i.e.

$$x_1' = \frac{x_2}{\sqrt{\beta_1\beta_2}\sin\phi_{21}} - \frac{\cot\phi_{21} + \alpha_1}{\beta_1} x_1. \tag{4}$$

where β_i and α_i, i=1,2, are the Twiss parameters at BPM1 and BPM2, respectively, ϕ_{21} is the phase advance between the two BPMs. Since

$$x_1^2 + (\beta_1 x_1' + \alpha_1 x_1)^2 = 2\beta_1 J, \tag{5}$$

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x_1 and x_2 satisfy the elliptical equation

$$x_1^2 + \left(\sqrt{\frac{\beta_1}{\beta_2}} \frac{x_2}{\sin\phi_{21}} - \cot\phi_{21} x_1\right)^2 = 2\beta_1 J. \qquad (6)$$

where J is the action. Hence, the ratio of the betatron functions $\sqrt{\frac{\beta_1}{\beta_2}}$, the phase advance between the two BPMs ϕ_{21} and $\beta_1 J$ can be obtained by fitting the turn-by-turn data of the two BPMs[3, 4, 5]. In accelerators with many BPMs distributed around the ring, turn by turn beam position data at all the BPMs can be measured simultaneously which then allows one to derive betatron functions around the ring.

2.2 *Measure the detuning effect*

The octupole and sextupole's field generate detuning effect, in which different particles with different betatron oscillation amplitude have different tunes

$$\nu_z = \nu_{z0} + \frac{1}{2}\alpha a^2, \qquad (7)$$

where ν_{z0} is the betatron tune of the center particle and a is the betatron oscillation amplitude. In the presence of detuning, the simple linear relation of Eq.(2) no longer holds. The top part of Fig. 2 shows the fixed points as a function of the proximity parameter $\delta = \nu_m - \nu_z$ [6]. Two islands are developed after the bifurcation point as shown in the bottom figure. The detuning coefficient α can be measured by ramping the AC dipole frequency through the resonance and measuring the amplitude of the excited oscillation as a function of the modulation.

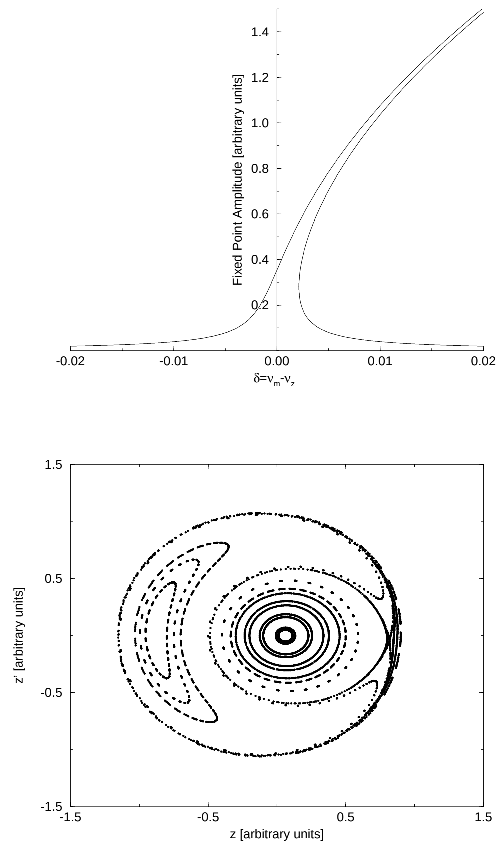

Figure 2: The top plot is the calculated fixed points as a function of the proximity parameter δ. The bottom plot shows the phase plot in the rotating frame, namely the frame which rotates along with the modulation frequency.

2.3 *Other applications*

- Measure the nonlinear harmonics of the one turn Hamiltonian.
  In high energy colliders like RHIC and LHC, IR correction is one of the important issues to improve the luminosity. In order to meet this requirement, reliable measurements of the non-linear components in the accelerator is necessary. To achieve this, turn by turn BPM data of a sustained large amplitude coherent oscillation are desired. Unlike the linear case, the phase space is distorted due to the non-linearities in the machine. By analyzing the spectrum of the turn by turn beam position data, one can then extract the information of the non-linear components [7, 8, 9].

- Spin flipper.
  Beside the gold operation, another important project in RHIC is the polarized proton physics which often prefers to have collisions with different spin patterns to cancel systematic experimental errors. This requires one to reverse the polarization of the beam. In RHIC, polarized protons are acceleration with two snakes to eliminate all the first order spin resonances. So, in the presence of two snakes, spin flipping can be achieved by introducing a oscillating magnetic field to excite an artificial spin resonance. By slowly ramping its frequency through the spin precession frequency, a full spin flip can be obtained [10]. Fig. 3 is the tracking result of a single particle.

In RHIC, two AC dipoles will be installed in sector 3 between the D0 magnet and the interaction point. The betatron functions at the AC dipole location are about 11 m. Both magnets are about 1 m long. Table 1 lists their design parameters.

In order to minimize power losses, the AC dipole is designed as an air-core magnet using Litz wire. Unlike regular conductor, Litz wire consists of thousands of fine strands. Its AC resistance is greatly reduced

3 CONCLUSION

A sustained coherent oscillation with large amplitude can be adiabatically excited by an AC dipole preserving the emittance. This method has been successfully applied in the AGS polarized proton acceleration to overcome

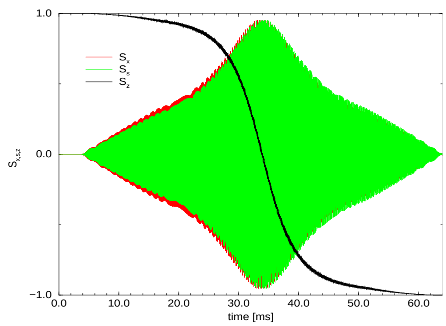

Figure 3: Spin tracking of 1000 particles using an AC dipole to induce a spin flip. The nominal spin tune in RHIC is $\frac{1}{2}$. In this particular case, we moved the spin tune slightly away from its nominal value by tuning the two snakes' axis. The AC dipole strength is 500G-m and its modulation tune was swept from 0.443 to 0.457 in 2700 turns.

Table 1: Margin specifications

field	application	desired B [G-m]	resonant frequency	maximum coherence
Hori.	nonlinear beam dynamic studies	380	63.95 kHz	5σ
	betatron function measurement	78		1σ
	spin flipper	100	37.5 kHz	-
vert.	beam studies	380	63.73 kHz	5σ
	betatron function measurement	78		1σ

strong intrinsic spin depolarizing resonances. As a non-destructive method, several other other applications in beam diagnostics and dynamics studies, spin manipulations have been proposed.

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